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PERFORMANCE PARAMETER FOR BIO EPOXY RESIN: AN OVERVIEW

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ABSTRACT

In recent years, the increasing awareness of the environmental and health impacts of petroleum-based materials has spurred significant research into bio-based epoxy resins. Derived from renewable biomass sources, these resins offer a sustainable alternative to traditional petroleum-based epoxies, addressing concerns over resource depletion, environmental pollution, and harmful industrial processes. Bio-based resins, synthesized from materials like plant oils, starches, lignin, and food waste, have garnered attention for their potential to reduce reliance on fossil fuels while delivering comparable or superior mechanical, thermal, and chemical properties. Research has focused on overcoming challenges related to brittleness, cost, and compatibility with reinforcing fibers. Additionally, incorporating bio-based components like cashew nut shell liquid ,vegetable oils, and natural fibers has led to the development of innovative bio-epoxy composites with enhanced sustainability and functionality. Advances in bio-based epoxy resins also include the design of systems with unique features such as self-healing abilities, improved mechanical properties, and resistance to extreme conditions, meeting the growing performance demands in industries like automotive, aerospace, and construction.

KEYWORDS: Bio Epoxy Resin, Epoxidation, Glass Transition Temperature, Tensile Strength

1. INTRODUCTION

Bio epoxy resin is a kind of epoxy resin that is made entirely or in part from biological, renewable resources like lignin, plant oils, and other agricultural waste. By employing sustainable natural raw materials, bio epoxy resins seek to lessen their environmental impact in contrast to conventional epoxy resins, which are usually made from chemicals derived from petroleum. These resins offer better biodegradability and a lower carbon footprint while retaining many of the desirable qualities of conventional epoxies, such as high strength, superior adhesion, and chemical resistance. Applications for them are growing in the automotive, aerospace, and construction sectors, ranging from composites to coatings and adhesives. Bio epoxy resins play a significant role in the global movement to use greener materials in manufacturing, assisting in the reduction of dependency on fossil fuels and the advancement of environmental sustainability. An important development in the search for sustainable materials is bio epoxy resins. Bio-based resins have the potential to significantly alter how we design and produce goods as industries around the world transition to carbon neutrality and circular economies. Fundamentally, bio epoxy resins are not merely a more environmentally friendly choice; rather, they mark the beginning of a new era of high-performance, environmentally friendly materials that meet future environmental and technological requirements.

1.1. Soybean Oil Based Epoxy Resins

soybean oil-based epoxy resins are sustainable materials derived from renewable resources, synthesized by chemically modifying the unsaturated bonds in soybean oil to produce epoxidized soybean oil (ESO). Valued for their biodegradability, low toxicity, and environmental benefits, these bio-based resins are explored for use in coatings, adhesives, composites, and electronics. However, limitations in rigidity and thermal stability have prompted ongoing research into structural enhancements and hybrid formulations.

1.2. Cardanol Based Epoxy Resins

Cardanol-based epoxy resins are sustainable polymers derived from cardanol, a renewable phenolic compound from cashew nut shell liquid (CNSL). With modifiable hydroxyl and aliphatic groups, cardanol is converted into epoxy monomers via epoxidation or glycidylation. These resins offer good thermal stability, chemical resistance, and flexibility, serving as eco-friendly alternatives to petroleum-based epoxies in coatings, adhesives, composites, and electronics.

1.3. Furan Based Epoxy Resins

Furan-based epoxy resins are bio-based polymers derived from biomass-sourced furan compounds like furfural and HMF. These monomers, modified to introduce epoxy functionality, yield resins with excellent thermal stability, chemical resistance, and rigidity due to the furan ring structure. Offering a sustainable alternative to bisphenol-A-based epoxies, furan-based resins are suited for coatings, adhesives, and composites in high-performance, eco-conscious applications.

1.4. Rosin Based Epoxy Resins

Rosin-based epoxy resins are renewable polymers derived from pine resin components like abietic acid, featuring a rigid tricyclic structure ideal for chemical modification. Through esterification or glycidylation, rosin can be transformed into epoxy monomers with excellent thermal stability, hardness, and adhesion. These bio-based resins offer a non-toxic, sustainable alternative to petroleum-based epoxies for use in coatings, adhesives, and composites.

1.5. Lignin Based Epoxy Resins

Lignin-based epoxy resins are sustainable polymers derived from lignin, an abundant aromatic biopolymer found in plant cell walls. Rich in hydroxyl and methoxy groups, lignin can be chemically modified into epoxy monomers via epoxidation or glycidylation. These resins offer high thermal stability, good mechanical strength, and biodegradability, making them promising green alternatives for coatings, adhesives, and composites.some bio epoxy resin discussed here with.

1.6. Itaconic Acid Based Epoxy Resins

Itaconic acid-based epoxy resins are sustainable polymers synthesized from itaconic acid, a bio-derived unsaturated dicarboxylic acid produced via fermentation. With reactive carboxyl and double bonds, itaconic acid enables efficient functionalization into high-performance epoxy resins. These materials offer strong mechanical properties, chemical resistance, and thermal stability, making them eco-friendly alternatives for use in coatings, adhesives, and composites.

1.7. Gallic Acid Based Epoxy Resin

Gallic acid-based epoxy resins are bio-based polymers derived from gallic acid, a natural polyphenol rich in reactive hydroxyl and carboxyl groups. Through chemical modifications like glycidylation, gallic acid is transformed into multifunctional epoxy monomers with high aromatic content. These resins offer excellent thermal stability, flame retardancy, and antioxidant properties, making them suitable for sustainable, high-performance applications in coatings, adhesives, and electronics.

1.8 Vanillin Based Epoxy Resin

Vanillin-based epoxy resins are sustainable polymers derived from vanillin, an aromatic compound sourced from lignin or other renewables. With reactive aldehyde, hydroxyl, and methoxy groups, vanillin can be functionalized—typically via glycidylation—into epoxy monomers. These resins offer good thermal stability, rigidity, and low toxicity, making them promising BPA-free alternatives for use in coatings, adhesives, and composites.

1.9 Isosorbide Based Epoxy Resin

Isosorbide-based epoxy resins are sustainable polymers derived from isosorbide, a bicyclic diol sourced from renewable resources like corn starch. With two hydroxyl groups on a rigid backbone, isosorbide is ideal for epoxy resin synthesis, offering excellent thermal stability, mechanical strength, and chemical resistance. These resins are eco-friendly alternatives to petroleum-based epoxies, with applications in coatings, adhesives, and composites, aligning with the shift towards sustainable materials.

1.10. Cinnamic Acid Based Epoxy Resin

Cinnamic acid-based epoxy resins are bio-based polymers derived from cinnamic acid, an aromatic carboxylic acid found in plants like cinnamon. Featuring a conjugated carboxyl group and alkene, cinnamic acid can be converted into epoxy monomers through reactions like esterification or glycidylation. These resins offer excellent mechanical properties, thermal stability, and UV resistance, making them a sustainable alternative to petroleum-based epoxies for use in coatings, adhesives, and composites.

1.11 Catechin Based Epoxy Resin

Catechin-based epoxy resins are bio-derived polymers synthesized from catechin, a flavonoid found in tea leaves. With multiple hydroxyl groups and an aromatic ring, catechin is highly reactive and can be modified to produce epoxy resins. These resins offer excellent antioxidant properties, thermal stability, and mechanical strength, making them ideal for coatings, adhesives, and composites. As a renewable, non-toxic alternative to petroleum-based epoxies, catechin-based resins support the demand for sustainable, eco-friendly materials.

1.12. Eugenol Based Epoxy Resin

Eugenol-based epoxy resins are bio-based polymers derived from eugenol, a phenolic compound found in clove oil, nutmeg, and cinnamon. With a phenolic group and a double bond, eugenol is easily modified to produce epoxy monomers through glycidylation or epoxidation. These resins offer high thermal stability, strong mechanical properties, and chemical resistance, making them sustainable alternatives to petroleum-based epoxies for applications in coatings, adhesives, and composites.

1.13. Sugar Based Epoxy Resin

Sugar-based epoxy resins are bio-based polymers derived from renewable sugars like glucose, fructose, or sucrose. Through chemical modifications such as glycidylation or esterification, these sugars are converted into epoxy resins. Offering excellent mechanical strength, thermal stability, and biodegradability, sugar-based epoxies are sustainable alternatives to petroleum-based resins, with applications in coatings, adhesives, and composites.

1.14. Pine Resin-Based Epoxy Resins

Derived from pine trees, particularly the resin (or rosin) secreted by pine trees, these epoxy resins offer good adhesion, thermal stability, and water resistance. Pine resin-based epoxy resins are widely used in coatings, adhesives, and as modifiers for other resins.

1.15. Phenolic Resin-Based Epoxy Resins

Phenolic resins, obtained from phenolic compounds found in plants, can be chemically modified to form epoxy resins. These resins offer excellent flame resistance, chemical resistance, and thermal stability, making them ideal for industrial coatings, automotive applications, and electrical insulations.

1.16 Terephthalic Acid-Based Epoxy Resins
Derived from renewable sources of bio-based terephthalic acid (such as through fermentation), these resins can be used in various coating, adhesive, and composite applications. They offer high mechanical strength and good environmental stability.

1.17. Algae-Based Epoxy Resins
Algae, specifically microalgae, are becoming a promising source for the production of bio-based chemicals, including epoxy resins. Algae-based epoxies are renewable, biodegradable, and have potential applications in coatings, composites, and even biomedical devices, as they offer unique characteristics like flexibility and low environmental impact.

1.18. Castor Oil-Based Epoxy Resins
Castor oil, a vegetable oil from the castor bean plant, contains a high percentage of ricinoleic acid, which can be epoxidized to form epoxy resins. These resins are used in coatings, adhesives, and composites and offer flexibility, moisture resistance, and good mechanical properties.

1.19. Tannin-Based Epoxy Resins
Tannins, polyphenolic compounds found in oak, chestnut, and other plants, can be used to create bio-based epoxy resins. These resins have antioxidant properties, good mechanical strength, and are used in coatings, adhesives, and even in the leather industry.

1.20. Dimer Acid-Based Epoxy Resins
Dimer acids, which are dimerized fatty acids typically derived from vegetable oils, can be used to create epoxy resins. These resins are known for their chemical resistance, high viscosity, and are often used in coatings, adhesives, and industrial applications.

1.21. Cork-BasedEpoxyResins
Cork, a natural material harvested from the bark of cork oak trees, contains compounds that can be used to synthesize bio-based epoxy resins. These resins have the potential for lightweight and durable applications in automotive, packaging, and construction industries.

1.22. Bio-BasedBisphenolA(BPA)-FreeEpoxyResins
These resins are created by replacing the traditional bisphenol A (BPA) with bio-based alternatives, such as bisphenol S (BPS) derived from renewable resources. This offers the same performance as traditional epoxies but with less environmental impact, often used in coatings, electronics, and adhesives.

1.23. MannichBaseEpoxyResins
These resins are formed by reacting phenolic compounds (often derived from biomass sources) with amines and formaldehyde. Mannich-based epoxy resins offer enhanced mechanical properties and are used in a range of applications, including automotive coatings and construction materials.

1.24. EpoxidizedNaturalRubber(ENR)EpoxyResins
Derived from natural rubber, epoxidized natural rubber can be chemically modified to form bio-based epoxy resins. These resins exhibit flexibility, high elasticity, and good chemical resistance, making them suitable for specialty coatings, adhesives, and elastomeric applications. Attempt of various researchers are discussed below.

2. REVIEWS VARIOUS RESEARCHERS
Mustapha et al [1]. highlight soybean, linseed, and hemp oils as promising sources for sustainable epoxy systems. Triglyceride-based oils like coconut, soybean, and palm can yield glycerol, used in both commercial resin production and epoxy synthesis. Additionally, non-edible oils such as castor, karanja, and canola are being explored for their potential in this context.

Chen et al. [2] developed fully bio-based epoxy systems by esterifying eugenol with various diacid chlorides and employing allylic bond oxidation followed by self-curing, resulting in improved thermoset rigidity and increased T5% compared to DDM-cured systems.

Pansumdaeng et al. [3] developed a fully bio-based epoxy system using epoxidized soybean oil and bio-based crosslinkers (SUC, SU, SE), showing strong potential for triboelectric nanogenerators. While the system offers flexibility and excellent hydrophobicity (1% water uptake after one day), its low tensile strength and modulus (0.2 and 1.5 MPa) limit its use in structural composites, making it more suitable for flexible coatings.

Busturk et al. [4] developed UV-curable organic–inorganic hybrid coatings from methacrylated and phosphorylated epoxidized soybean oil using sol-gel processing. The resulting materials are hydrophobic, biodegradable, low-cost, and offer a promising balance of physical and mechanical properties.

K. P. Unnikrishnan et al. [5] synthesized epoxidized cardanol oil (ECO) using epichlorohydrin and NaOH, with cardanol derived from cashew nut shell liquid via vacuum distillation. ECO, available commercially, serves as a renewable substitute for phenol-based resins, offering hydrophobicity due to its aliphatic side chains—an asset for various applications.

Kai et al. [6] synthesized low-viscosity, liquid epoxy resins BOF (furan-based) and BOB (benzene-based), cured with PACM and EPIKURE W. The BOF thermoset showed higher Tg and storage modulus due to restricted furan ring rotation and enhanced hydrogen bonding, suggesting furan—readily derived from biomass—as a strong bio-based alternative to petroleum-based resins.

Rasha et al. [7] synthesized a rosin-based epoxy resin, tetraglycidyl dimaleopimaryl ketone (TGK), via a multi-step process from isomerized abietic acid. When cured with rosin (RC) or p-phenylenediamine (PPD), TGK exhibited higher Tg than commercial DGEBA/PPD systems due to restricted polymer chain mobility. TGK/RC also showed superior thermal stability and comparable storage modulus, making it a strong candidate for coating applications.

Fatemeh et al. [8] synthesized lignin-based epoxy resins from depolymerized organosolv (DOL) and kraft lignin (DKL) using epichlorohydrin and TBAB as a catalyst. When cured with DDM and DETA, the DDM-cured DKL resin showed notable thermal stability (290 °C), highlighting lignin's potential in sustainable epoxy systems.

Songq et al. [9] synthesized an itaconic acid-based epoxy resin (EIA) via esterification with epichlorohydrin using TBAB and NaOH. EIA showed a high epoxy value (0.625) and superior curing reactivity with MHHPA. The cured resin exhibited excellent thermal and mechanical properties (Tg 130 °C, tensile strength 87.5 MPa), outperforming or matching DGEBA-based systems.

Aouf et al. [10] synthesized a bio-based epoxy resin from gallic acid via allylation and epoxidation, producing glycidyl ether of gallic acid (GEGA). When cured with IPDA, GEGA exhibited a significantly higher Tg (233 °C) than DGEBA (160 °C), due to its greater crosslink density and functionality. GEGA also serves as a reactive dispersant for graphene, enhancing dispersion and interfacial bonding in epoxy composites.

Xin et al. [11] synthesized a cinnamic acid-based liquid epoxy resin (Cin-epoxy) with lower viscosity (0.67 Pa·s) than DER332 (3.31 Pa·s), indicating better processability. The resin, synthesized via Friedel-Crafts reaction, allylation, and epoxidation, was cured with various anhydrides (DPMA, HHPA, MNA). Cin-epoxy cured with MNA exhibited higher curing reactivity than DER332, with similar thermal stability. The Cin-epoxy/MNA system showed comparable thermal stability to DER332/MNA and outperformed DPMA-cured systems, positioning Cin-epoxy as a viable bio-based alternative to petroleum-based epoxies.

Basnet et al. [12] reported that catechin-based epoxy resin, cured with natural agents like lignin, exhibited a higher Tg, excellent chemical resistance, and high flexural strength. Its thermal degradation (5% weight loss) was slightly lower than that of bisphenol-based epoxy resins, making it suitable for electronic materials.

Qin et al. [13] synthesized di-functional eugenol-based epoxy resins (EU-EP) through epoxidation and glycidylation of phenolic groups. EU-EP, solid with low melting point and higher purity, showed similar curing reactivity, thermal stability, and mechanical properties to DER353 epoxy resin cured with HHPA. When cured with bio-based rosin-anhydride (MPA), EU-EP exhibited a higher Tg (155 °C) than HHPA-cured DER353 (106 °C), demonstrating comparable properties to petroleum-based systems.

Rapi et al. [14] synthesized a series of bi- to tetrafuctional epoxy resins from D-glucose, including α-glucopyranoside and α-glucofuranoside derivatives. Cured with DDM, the trifunctional resins showed favorable properties for high-tech applications, as confirmed by DSC and TGA studies.

B. Phettong and L. Mezeix et al.[15] investigates bio-epoxy materials as sustainable alternatives to petroleum-based resins in the aeronautical industry. Three bio-epoxy resins were tested: two non-recyclable (YDL 5551 and YDL 5561) and one recyclable (YDL 5544). Moisture absorption tests showed YDL 5561 had the highest absorption, while mechanical tests revealed it outperformed the others in tensile strength, yield strength, and elongation due to its higher bio-based carbon content. YDL 5544 also showed promising properties for sustainable aerospace applications. The comparison of Young's modulus, yield strength, and elongation (Figure 2) highlighted YDL 5561 as the highest performing resin with 48.9% bio-based content. These results emphasize the potential of bio-epoxy materials for aerospace, advancing the development of environmentally friendly and recyclable solutions. Further research could improve the performance and recyclability of these materials.

Laurent Mezeix et al.[16] The aerospace industry's reliance on composites highlights the need for sustainable alternatives to petroleum-based epoxy resins, which are harmful and non-degradable. Bio-sourced carbon epoxies, made from vegetable oils or bio-based copolymers, offer a promising solution. This study evaluates the mechanical properties of conventional, recyclable, and non-recyclable bio-epoxies through various tests. Results show that recyclable bio-epoxies, especially E Recy (27% bio-content), offer comparable or superior properties, including a 73% higher strain energy release rate than conventional epoxies. The study also compares four epoxy systems, laying the groundwork for future research on bio-epoxies in aerospace. Future studies will focus on moisture absorption and composite laminate testing to assess damage tolerance and mechanical performance, contributing to the development of more sustainable and durable aerospace materials.

Gökhan DEMİRCAN et al [17]epoxy resins, commonly used in industries such as painting, bonding, and coating, are thermosetting resins known for their high mechanical properties. They serve as matrix materials in composite production, combined with fibers like glass, carbon, or aramid for aerospace, marine, and aviation applications. Traditionally, most epoxy resins are petroleum-based. However, there is a growing emphasis on bio-based plant materials to reduce petroleum dependence and utilize abundant, cost-effective plant resources. This study explores the production of a bio-based epoxy resin by combining petroleum-based epoxy with rosin from wood resin, examining their mechanical and thermal properties.

Nithesh Naik et al.[18] The growing awareness of environmental concerns and depleting petroleum resources has driven research into sustainable materials from renewable sources. Natural bio-based polymers are replacing synthetic ones due to their environmental benefits. Cardanol, derived from cashew nutshell liquid (CNSL), is a promising bio-based component for epoxy production. This study investigates the mechanical properties of three cardanol-based bio-epoxies, focusing on Vickers hardness, tensile, flexural strength, and water absorption. Among the variants, FormuLITE 2, containing 34%

bio-content, showed highest mechanical performance and water absorption the rate comparable to conventional LY556/HY951 epoxy. Thus, FormuLITE 2 is identified as the best bio-based epoxy for use as a matrix material in biocomposite fabrication.

William E. Dyer et al [19]. Epoxy resins, used for over 50 years as composite matrix materials, offer high strength, chemical resistance, and ease of processing. However, their reliance on non-renewable feedstocks poses sustainability challenges. While bio-based alternatives have been explored, they often fall short of industry standards in performance. This study compares three bio-based epoxy monomers with three petroleum-derived industry standards. Resin systems were synthesized using an industrial high-performance aromatic diamine hardener, and their tensile, flexural, and fracture toughness properties were evaluated. Free volume analysis using positron annihilation lifetime spectroscopy (PALS) revealed a correlation between flexural modulus and free volume, with more aromatic thermoset resins showing higher stiffness. Among the bio-based options, vanillyl alcohol diglycidyl ether (VDE) exhibited the highest tensile strength, flexural modulus, and fracture toughness, outperforming traditional options like BADGE. Further research is needed into processing behavior, fracture toughness, and lifecycle assessments to evaluate bio-based resins for industrial-scale applications. How raw natural oil epoxidised and their equation of mechanism discussed below.

3. VEGETABLE OIL EPOXIDATION

Vegetable Oils Epoxidized (VOE) are used as plasticizers and stabilizers for polyvinyl chloride and other plastics. These become flexible and sufficient to be used for the production of packaging films. They meet the requirements for high temperature lubrication and are easily biodegradable. A high reactivity of the oxirane ring in the oils causes their transformation into alcohols, polyols, glycol mono esters, glycol diesters, carbonyl compound and epoxy polymers.

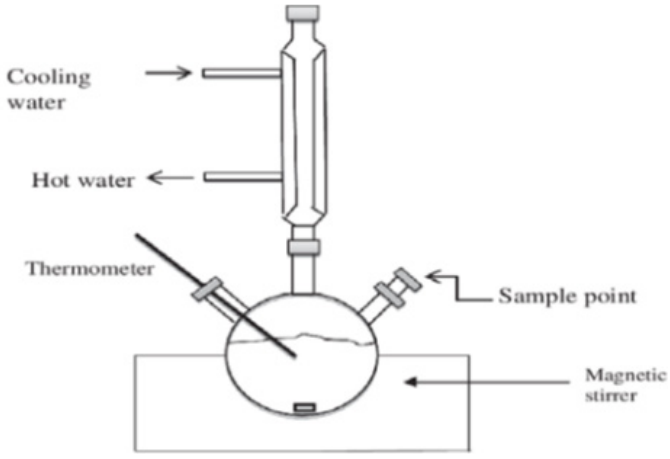

Fig 1. Expérimental setup for oils epoxidation [6]

Weigh the appropriate amount of vegetable oil and transfer it into a round-bottom flask. Add the solvent , Add the catalyst (Addition of Oxidizing Agent, For hydrogen peroxide (H_2O_2), it can be added similarly or mixed with a catalyst to enhance the reaction rate as shown in figure 1, Heat the mixture under reflux at a temperature between 60–80°C for several hours (typically 4–6 hours). Stir the mixture continuously to ensure homogeneous mixing. The reaction should be monitored regularly by titration or by checking the disappearance of the carbon-carbon double bonds in the oil (via FTIR spectroscopy or a thiol titration method). Once the reaction is complete (when all double bonds have been epoxidized), cool the mixture to room temperature. Neutralize the reaction mixture if needed using a weak base (e.g., sodium bicarbonate) to remove any remaining acid. Extract the product using diethyl ether or hexane if a solvent was used. Wash the organic phase with water to remove any residual oxidizing agent or catalyst. Dry the organic phase over anhydrous sodium sulfate (Na_2SO_4) and evaporate the solvent under reduced pressure to obtain the epoxidized oil. If needed, purify the epoxidized oil by column chromatography or vacuum distillation to remove impurities or unreacted material. general equation of mechanism for natural oil for epoxidation shown in figure 2.

Triglycerides → Epoxidation → Epoxidized Oil → Curing → Bio-Epoxy Resin

Epoxied groups+ hardeners (amines/anhydrides)=curing (crosslinked network)

Figure 2. Equation of mechanism

4. DISCUSSION :

soybean oil (ESO) in thermosetting polymers Enhanced tensile strength, rising from 2.8 MPa to 34.0 MPa, Improved thermal and shape memory performance, with the glass transition temperature increasing from 16.9 °C (TL-0) to 118.6 °C (TL-50), along with enhanced shape fixation (from 89.1% to 94.0%) and recovery ratios (from 89.5% to 99.3%). Reduced thermal stability, yet with a notable increase in char yield at 800 °C, suggesting better flame resistance.[22] Cardanol-based epoxy and novolac resins (with bio-contents of 65% and 84%, respectively) were blended Comparable tensile properties to traditional formulations, even with up to 40% bio-content. Suitable glass transition temperature (Tg) for automotive applications. Enhanced flexibility and viscoelastic behavior with increased bio-content. [23] furan-based hardener (DFA). High glass transition temperature (Tg) of 171 °C, ensuring thermal stability. Strong mechanical properties, with a tensile strength of 62.9 MPa and a storage modulus of 2,356 MPa. Inherent anti-flammability, achieving a UL-94 V-0 rating and a high LOI of 36.0%. [24] the study examined the natural rosin resin and hybrid resins with varying rosin content (45%, 55%, and 65%). Increasing rosin content led to a decrease in stiffness and strength. The viscoelastic behavior of the hybrids became more pronounced with higher rosin volumes.[25] industrial alkali lignin to create low-carbon, environmentally friendly bio-based epoxy thermosetting materials. Epoxidized lignin was combined with petroleum-based bisphenol A tensile strength of 4.6 MPa and an elongation at break of 315.5% [26] itaconic acid (IA)-based epoxy resin (EIA) was synthesized through esterification with epichlorohydrin (ECH), Higher epoxy value (0.625) and greater curing reactivity of EIA compared to the commonly used DGEBA. The mechanical properties of the cured EIA were comparable to or better than those of DGEBA, with a glass transition temperature of 130.4

°C, tensile strength of 87.5 MPa, flexural strength of 152.4 MPa, and modulus of 3400 MPa.[27] gallic acid-based epoxy vitrimer (GA-EP) ,A high glass transition temperature (Tg) of 122 °C, along with satisfactory mechanical, thermal, and degradation properties. Comparable performance to traditional Bisphenol A-based epoxy vitrimers. [28] A vanillin-based epoxy resin (VH-HDA-EP) was synthesized from vanillin, 1,6-hexanediamine, and epichlorohydrin, featuring a rigid Schiff base structure and flexible alkane segments. Superior flame retardancy, with a limiting oxygen index of 38.5% and passing the UL-94 V-0 test. Enhanced thermal stability, with a char yield of 30.8 wt% (compared to DGEBA's 17.9 wt%). Significant reduction in heat release (45.1%), smoke production (73.4%), and maximal smoke density (36.2%). Improved mechanical properties, with storage modulus of 2821 MPa, glass transition temperature of 186 °C, tensile strength of 55.6 MPa, and elongation at break of 8.3%. [29] isosorbide and succinic anhydride and cured with the bio-based amine 1,8-p-Menthanediamine (MTDA) to form a solid thermoset. The flexible succinic segments in ISSATE lowered its glass transition temperature (Tg) compared to DGEBA, but the tetrafunctional design led to enhanced epoxy reactivity, tensile strength, and elongation at break due to increased density of reactive sites. [30] A cinnamic acid-based epoxy resin (Cin-epoxy) was synthesized, followed by curing with a dipentene-based anhydride curing agent (DPMA).Cin-epoxy exhibited slightly higher reactivity than bisphenol A-based epoxy DER 332. The cured Cin-epoxy displayed good dynamic mechanical properties and thermal stability.[31] Japanese green tea (Camellia sinensis), functionalized with epichlorohydrin under alkaline conditions Thermal and mechanical properties of the resulting bio-based epoxy network were evaluated, showing that it offers good thermal stability and mechanical performance. The thermal decomposition temperature (Td5) of the resin was above 300 °C, slightly lower than bisphenol-A (BPA)-derived resins, and its glass transition temperature (Tg) ranged from 155 to 178 °C. [32] eugenol-derived epoxy precursor (TEPEU) was developed, and when cured with 4,4′-diaminodiphenyl sulfone (DDS), it formed a flame-retardant bio-based epoxy system (TEPEU/DDS). with a glass transition temperature (Tg) of 294.5 °C and a char yield of 29.8% at 700 °C in nitrogen. Superior fire resistance, with a limiting oxygen index (LOI) of 28.7% and total heat release (THR) of 15.9 $kJ \cdot g^{-1}$. Remarkable mechanical properties, including a storage modulus of 4.091 GPa, Young's modulus of 4.693 GPa, and hardness of 0.407 GPa, all significantly higher than those of DGEBA (bisphenol-A-based epoxy) cured with DDS. [33] Isosorbide, a renewable sugar derivative, was used to create epoxy thermosets that were functionalized with silica-forming mixtures, resulting in hybrid organic-inorganic networks. The final epoxy-silica nanocomposite exhibited excellent thermo-mechanical properties, including Tonset of 327°C, Tg of 55.9°C, and Tα of 70.1°C, along with hydrophobicity (contact angle of 105°) .[34] epoxidized pine oil resin (EP) and furfural alcohol resin (FA), Achieved a 7% higher bond strength for CFRP (4.2 MPa) and 17% lower bond strength for GFRP (2.8 MPa). Produced a weak bond when directly used for bonding to concrete, likely due to concrete alkalinity affecting curing. However, FA resin showed excellent results when used to create prefabricated CFRP plates, achieving 5 MPa bond strength when bonded to concrete using conventional epoxy paste. Full-scale beams demonstrated a 18-54% increase in peak load and a 9-46% increase in yielding load, depending on the type of fibers and resin used, as well as the number of FRP layers. Increasing the number of FRP layers from one to two resulted in only a 13-21% increase in ultimate load. [35] bio-phenolic/epoxy polymer blends to determine the best formulation for future research. The mechanical properties of the bio-phenolic/epoxy blends were found to be improved compared to neat epoxy and phenolic resins. No phase separation was observed in the polymer blends. The P-20 blend (20 wt% bio-phenolic and 80 wt% epoxy) exhibited the highest tensile, flexural, and impact strength. The P-25 blend (25 wt% bio-phenolic and 75 wt% epoxy) showed the highest tensile and flexural modulus. [36] the synthesis of aromatic epoxy resins derived from poly(ethylene terephthalate) (PET). The cured epoxy resins exhibited thermal stability up to 470 °C. Preliminary tests indicated that these resins have superior adhesion properties. [37] epoxidized phloroglucinol (PHTE) as a bio-based feedstock for epoxy resins, The cured PHTE–DDS resin showed a higher char yield (24% at 900 °C vs 1.3% for BADGE) and superior glass transition temperature (Tg) of 260 °C, compared to BADGE–DDS at 220 °C. PHTE–DDS exhibited enhanced mechanical performance, with improvements in flexural modulus.[38] using castor oil as a crosslinker, The tensile strength of composites with 15 wt% CN fibers in the presence of castor oil was found to be 35.98 N/mm^2 and 38.32 N/mm^2, indicating a significant strength improvement. Thermal analysis of the composites was carried out using Dynamic Mechanical Analysis (DMA). The glass transition temperature (Tg) and storage modulus of the castor oil-based composites were found to be higher than those of composites prepared without castor oil.[39] tannin-based epoxy resin (MTEBPE) derived from renewable tannin and epichlorohydrin feedstocks. The addition of 5 wt% MTEBPE to DGEBA significantly improved the mechanical properties of the thermosets, with tensile strength increasing by 35.8%, flexural strength increasing by 45.4%, impact strength increasing by 243.8%, and elongation at break increasing by 81.6% compared to neat DGEBA. the temperatures corresponding to 5% and 50% weight loss (T5% and T50%), as well as the char yield at 600 °C, were similar to neat DGEBA, indicating that the modification did not significantly affect the thermal stability of the resin. 40]

dimer acid diglycidyl ester (DAGE), a bio-based toughener, The incorporation of 5 wt% DAGE into DGEBA resulted in a 2.56 times increase in impact strength compared to neat DGEBA. Tensile strength and elongation at break also increased by 17.2% and 13.4%, respectively.[41] incorporating cork powder and different fibers, such as Kevlar and carbon fibers, in epoxy resin matrices. The addition of cork powder to the resin results in a 19.1 MPa difference in bending stress for Kevlar-reinforced composites compared to neat resin. The difference is 13.5% higher for laminates with cork-filled resin. When cork powder is added to the resin, the creep displacement increases by 24.6% achieving a maximum error of 0.6%, demonstrating its accuracy in predicting relaxation stress response. [42] using diphenolic acid (DPA) as a precursor, aiming to replace Bisphenol A

(BPA)Among the SA-cured epoxy resins, diglycidyl ether of diphenolic ethylamide showed the best performance, achieving: Glass transition temperature (Tg): 114 °C ,Char yield (CY): 20%, Tensile strength: 60.2 MPa, Toughness value: 185 MPa.[43] Mannich base epoxy resin (EPK-3251) cured with 9,9'-bis(4-hydroxyphenyl)anthrone-10 (EAN). The EPK-3251 cured resin is thermally stable up to 360°C and follows a first-order decomposition reaction, retaining 52.5% residue at 700°C, which indicates its strong thermal resistance. The equilibrium water absorption and diffusivity of the composites were influenced by the nature of the electrolytes in contact with them.[44] epoxidized natural rubber (ENR) blended with natural rubber (NR). with ENR compositions ranging from 0% to 100% rubber. The tensile strength and elongation at break of the blends were studied, with the blends comprising ENR 25 (25% epoxidation), ENR 50 (50% epoxidation), and SMR L. The composition of ENR in the blends was varied from 0% to 100%. tensile strength and elongation at break reached a maximum at 50% ENR in the blends of ENR 25/SMR L and ENR 50/SMR L. This reinforcing effect was more pronounced in ENR 25 blends due to the higher crystallinity and greater availability of double bonds, which enhanced the compatibility between ENR 25 and ENR 50, the impact of sulfur concentration on the retention of tensile properties after aging. sulfur concentration increased, the percentage retention of tensile strength decreased. This is because higher sulfur loading promotes the formation of polysulfidic cross-links, which are more prone to breakdown during aging.[45]

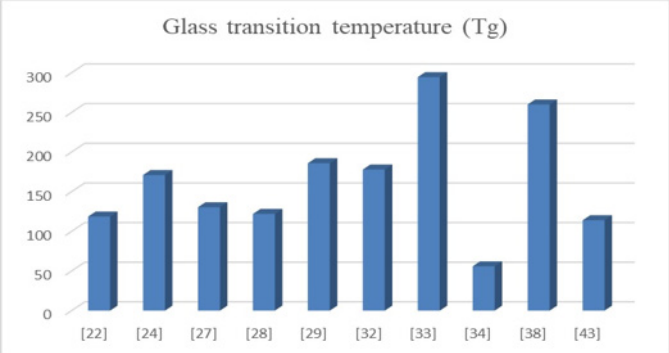

Fig 3. reviewed glass transition temperature Tg

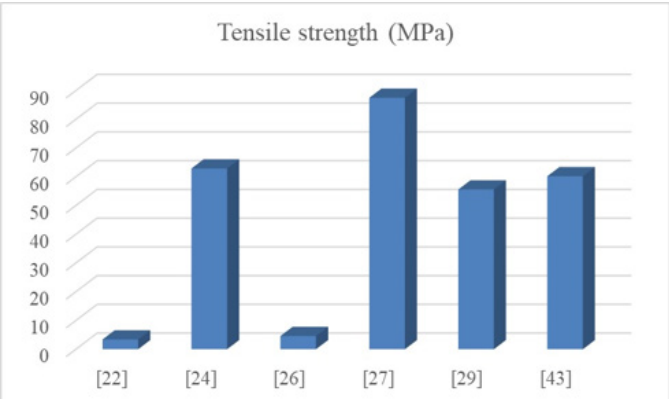

Fig 4. reviewed tensile strength

5. COCLUSION

Chemical bonding or cross linking densities of various bio epoxy resin based on molecular structure ,curing agent and degree of crosslinking .temperature rises increases cross linking density which directly impact tensile strength of bio epoxy resin as shown in figure 3 and 4. optimized crosslinking density and stronger intermolecular forces play important role, moderate curing temperature enhance properties. glass transition temperature approached towards more rubbery of flexible state,higher Tg allow morw crosslinked network which resist deformation and crack propogation provide higher mechanical strength. Blending with other bio based material,change in chemical structure ,adding bio based nanofiller and curing agent play vital role of various application.

6. FUTURE SCOPE

Despite the progress in bio-epoxy research, challenges remain, particularly in the areas of fiber-matrix adhesion, water absorption, and mechanical performance.. Moisture absorption could affect long-term performance, particularly for aerospace applications where durability is critical. Recyclable bio-epoxies (e.g., YDL 5544, E Recy) show promise in reducing environmental impact, though more research is needed to assess their full potential. More focus on moisture absorption, composite laminate testing, damage tolerance, fracture toughness, and lifecycle assessments for bio-based resins to fully replace petroleum-based systems in high-performance applications. New biomaterial should be examined, advance synthesis method, life cycle assessment for environmental impact

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